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Meteorites recovered from Australia

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Abstract

Meteorites are our only tangible source of information on the earliest history of the Solar System. Over the last ten years the number of meteorites described from Australia has doubled, and this has stimulated many new lines of enquiry. To date, fragments from a total of 474 distinct and authenticated meteorites have been recovered in Australia. The material, including 13 meteorites observed to fall, comprises 389 stones (21 achondrites, 366 chondrites and 2 unclassified stones), 71 irons, 13 stony-irons and one meteorite of unknown class. Two hundred and fifty-seven distinct meteorites are currently known from Western Australia, 123 from South Australia, 48 from New South Wales, 20 from Queensland, 12 from the Northern Territory, 10 from Victoria and 4 from Tasmania. Discoveries include the first lunar meteorite (a fragment of the Moon), Calcalong Creek, found outside of Antarctica. Five meteorites (Veevers [iron], Wolf Creek [iron], Henbury [iron], Boxhole [iron], and Dalgaranga [mesosiderite stony-iron]) are associated with craters. Another eighteen impact structures (lacking meteorites) are known in Australia and the country has one of the world's best preserved impact cratering records stretching back more than 500 million years. Most meteorites in Australia have been found in the Nullarbor Region, which for climatic and geological reasons is one of the most prolific areas of the world for meteorite recoveries outside of Antarctica. Since 1971, several thousand specimens of an as yet unknown total number of distinct meteorites have been recovered from the Nullarbor, including many rare types. ^{14}C terrestrial ages of Nullarbor meteorites combined with population statistics are providing important information about the number of meteorites falling with time. Moreover, weathering studies of ancient stony meteorite finds, and the stable isotopic composition of carbonate contamination derived from the Nullarbor limestones is yielding palaeoclimatic information for that region of Australia over the last 30,000 years.

Introduction

Meteorites are an unique source of information about the earliest history of the Solar System. Mostly fragments broken from small planetary bodies, called asteroids, in solar orbits between Mars and Jupiter, many meteorites have remained virtually unaltered since their formation 4.55 Ga ago. Some rare types of carbonaceous meteorite contain water and complex carbon compounds, including amino acids. These rocks may be similar to the original materials from which the Earth gained the water for its oceans, the gases for the atmosphere we breathe, and the building blocks of life. However, aside from the fundamental question of the origin of life, basic research on meteorites is helping us to understand many other aspects of our natural environment and history. Research on Australian meteorites essentially started with the publication by Haidinger (1861) of a description of two masses of the Cranbourne iron meteorite found in Victoria in 1854.

On numerous occasions in the past, meteorites found in Australia have been reviewed, or listed (*e.g.* Cooksey 1897; Anderson 1913; Prior 1923; Hodge-Smith 1939; Prior & Hey 1953; Hey 1966; Mason 1974; Gibbons 1977; Graham *et al.* 1985; Bevan 1992a). Most recently, Bevan (1992a) provided a comprehensive review of meteorite recovery in Australia. However, since the early 1990's there has been a surge in the recovery of meteorites in Australia that has opened up many new lines of research.

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Figure 1 shows the numbers of meteorites known at various times from Australia during the period 1897-1996. Mason (1974) documented a total of 184 distinct meteorites from Australia. During the period 1974-1992, data were published for 93 new Australian meteorites (Bevan 1992a). However, since the last review by Bevan (1992a), data for an additional 197 meteorites from Australia have appeared in the literature. This remarkable recovery rate is largely due to discoveries in the Western Australian and South Australian Nullarbor Region. For climatic and geological reasons, the Nullarbor Region is one of the most prolific desert areas of the world for meteorite recoveries outside of Antarctica (Bevan &

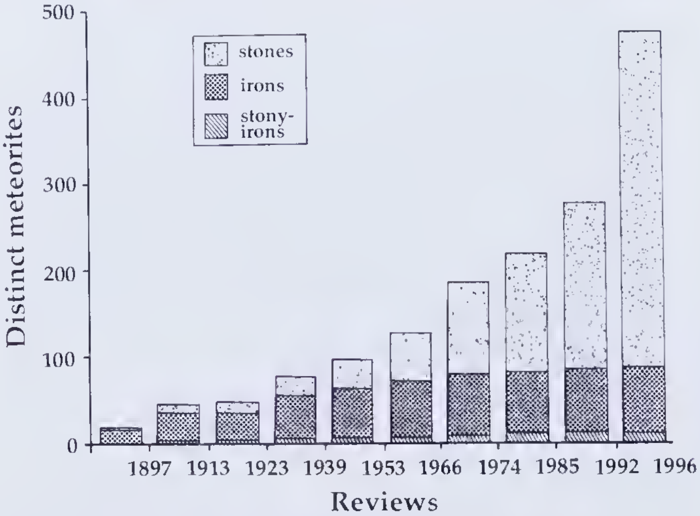

Figure 1. Cumulative histogram of meteorites known from Australia at various times during the period 1897-1996.

Binns 1989a,b,c; Bevan 1992a; Bevan & Pring 1993). Recoveries from the Nullarbor alone account for more than 50% of all meteorites currently known from Australia, and more than a thousand recently recovered, and potentially new, Nullarbor meteorite fragments remain to be described (Bevan 1992b; Koeberl *et al.* 1992).

The purpose of this paper is to review Australian meteorites, particularly those recovered since the last review by Bevan (1992a), and with special reference to the unique environment of the Nullarbor Region, to examine the climatic and physiographic factors that contribute to the recovery of meteorites in Australia.

Meteoritic materials and origin

Only a brief resumé of meteorite classification and genesis is presented here. For more detailed accounts, the reader is referred to the bibliography and references therein (*e.g.* Dodd 1981; McSween 1987).

Traditionally, meteorites have been divided into three major categories depending on the relative amounts of silicate and metallic minerals they contain. *Iron* meteorites are composed predominantly of iron-nickel metal; *stony* meteorites (often called 'stones') consist mainly of silicates, but also contain some metal and other accessory and minor mineral phases; and *stony-irons* comprise metal and silicates in roughly equal amounts. About 95% of modern observed meteorite falls are *stones*, around 4% are *irons* and only 1% are *stony-irons*. This simple classification scheme, however, conceals the diversity of materials that have fallen to Earth, and modern research has delineated numerous distinct groups and sub-types of meteorites.

Stones

Of the two main groups of stony meteorites recognised, the *chondrites* are the most numerous, accounting for 87% of all meteorites observed to fall. Chondrites contain millimetre-sized beads of stony minerals, called *chondrules*, from which the name of the group originates (Fig 2). Chondrules are unknown in any rocks from Earth and for more than a century arguments have continued over how these enigmatic objects might have formed. While there is still no consensus on the mechanism by which chondrules were generated, most researchers agree that chondrules were among the earliest materials to have formed in the Solar System. An understanding of the origin of chondrules, and subsequent chondrites, is fundamental to our understanding of how materials (and ultimately planets) formed in the infant Solar System. Chemical variations between chondritic meteorites define a number of distinct groups.

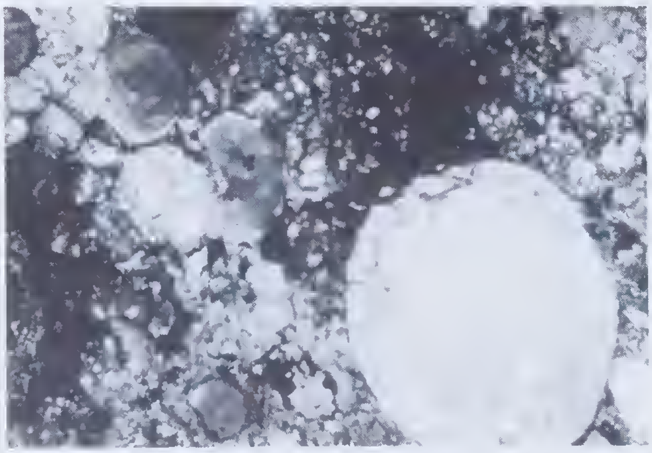

Figure 2. Photomicrograph of the Forrest Lakes LL5 ordinary chondrite showing numerous rounded chondrules.

The largest group, collectively known as the *ordinary chondrites*, accounts for more than half of all known meteorites (observed falls + chance finds) (*e.g.* see Fig 3). Although 75% of their bulk is made up of silicate minerals, ordinary chondrites contain substantial amounts of iron both in the form of silicates and as metal and iron-sulphide. Two other rarer groups of chondrite, *enstatite* and *carbonaceous chondrites*, represent extremes in composition. The enstatite chondrites are rich in metal and sulphide, but the main silicate mineral they contain (enstatite) is a pure magnesium-silicate containing no iron. In contrast, carbonaceous chondrites contain little or no metallic iron, but their silicate minerals are mostly iron-rich.

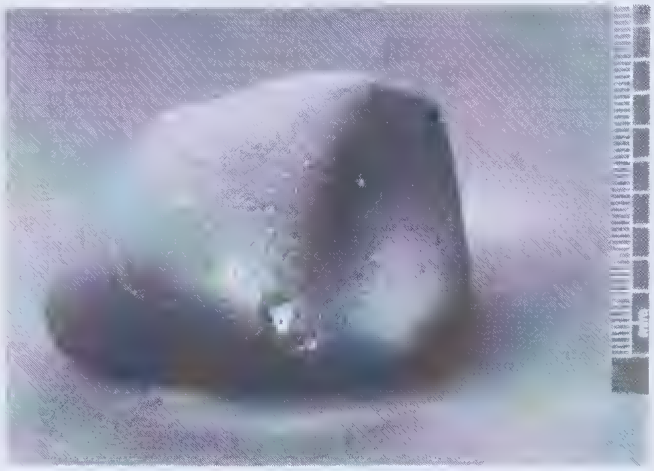

Figure 3. Mass of the ordinary chondritic (H5) meteorite that fell on Binningup beach, Western Australia, at 10:10 am on 30 September, 1984.

Carbonaceous chondrites are among the most important and intriguing classes of meteorites. Sometimes rich in complex carbon compounds such as amino and fatty acids, carbonaceous chondrites can also contain appreciable amounts of water (up to 20%), and water-bearing minerals that formed by the hydrothermal alteration of other minerals. A rare type of carbonaceous chondrite [CI], named for the type meteorite Ivuna (that fell in Tanzania), of which only a few are known, is composed almost entirely of minerals that formed at low temperatures. Significantly, some of these meteorites have chemistries that closely match the Sun's, and are our best samples of 'average' Solar System material. The majority of meteorites are believed to be fragmental debris from the collision of asteroids, but there is astronomical evidence suggesting that some carbonaceous chondrites may have had a cometary origin.

The *achondrites* make up around 8% of modern meteorite falls. So-called because they lack chondrules, achondrites generally have textures showing that they formed in similar ways to some of the igneous and volcanic rocks on Earth. Although most achondrites are asteroidal in origin, twelve are fragments of the Moon. These "lunar" meteorites were probably ejected from the Moon by large, low-angle impacts. We are able to recognise lunar meteorites by comparison with the reference collection of lunar rocks returned by the Apollo space missions and knowledge of the Moon's chemistry. Another twelve achondritic meteorites are planetary in origin and may be fragments of Mars (*e.g.* see Gladman *et al.* 1996 and references therein). Unlike meteorites of asteroidal origin, these meteorites crystallized only 200-1300 million years ago and must have come from a large, planetary-sized body that remained hot for much longer than the asteroids.

Irons

The chemical make-up of irons suggests that most solidified from molten accumulations of metal that could only have formed deep in the interiors of a number of small asteroids (Fig 4). Irons often consist of two iron-nickel minerals arranged in a regular trellis-work structure of interlocking crystal plates. When cut and polished surfaces of some irons are treated with acid, this structure, called a Widmanstätten pattern is revealed (Fig 5). Widmanstätten structures formed as the result of extremely slow cooling of hot metal in the solid state. Cooling rate calculations indicate that many irons are fragments of the cores of small asteroidal bodies ranging up to a few hundred kilometres in diameter. Like achondrites, most iron meteorites tell us that some bodies smaller than planets in the early Solar System melted and differentiated, separating metal from silicate to form 'cores' and 'crusts' like the Earth's. Other iron meteorites were never completely melted and some contain inclusions of silicate. The modern classification of irons is based on chemistry, notably the abundance of Ni, Ga, Ge and Ir that they contain.

Figure 5. Cut, polished and acid treated slice of the Haig iron meteorite showing the Widmanstätten pattern characteristic of this group of irons (sawn edge measures 8 cm).

Stony-irons

Stony-irons are by far the rarest of the main categories of meteorites. Two main groups of stony-irons are recognised. Meteorites of the largest group, the *pallasites*, are composed of crystals of olivine set in metallic iron-nickel. Members of the other major group of stony-irons, called *mesosiderites*, are made up of mixtures of fragments of rock similar to some achondrites in composition, and nuggets and veins of iron-nickel metal. There are also several anomalous meteorites (*e.g.* Bencubbin) that fit structurally into the stony-iron category, although these have no relationship to the two major groups. Bencubbin is a complex mixture of metal and silicate components, including a variety of chondritic xenoliths an example of which is seen as a dark area on the cut face of the meteorite (Fig 6). Bencubbin is not related to any of the known major groups of meteorites although some components are chemically and isotopically

Figure 4. Main mass, weighing 480 kg, of the Haig (group IIIAB) iron meteorite found on the Nullarbor Plain by Mr A J Carlisle in 1951 (photograph by D. Elford).

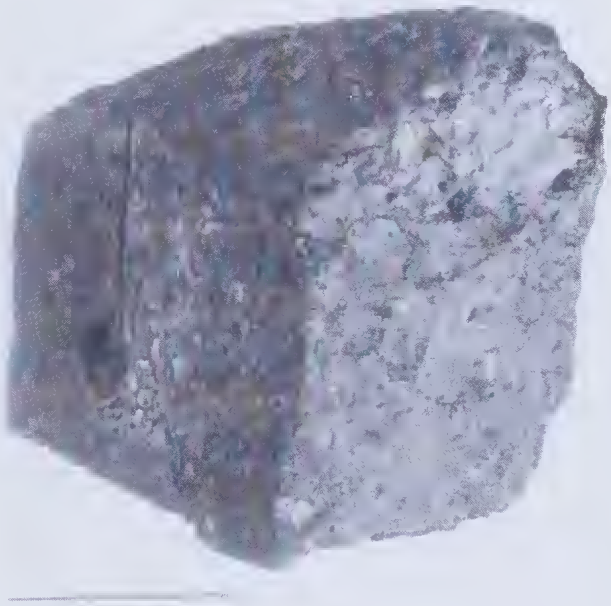

Figure 6. Mass (originally 54 kg) of the Bencubbin meteorite found in July 1930. Scale bar is 10 cm. (photograph by K Brimmell).

similar to the CR group of carbonaceous chondrites and an unique Antarctic chondrite Allan Hills 85085 (Barber & Hutchison 1991; Weisberg *et al.* 1995).

The stony-irons may have formed by the mixing of both solid and liquid metal and silicates at various depths within their parent asteroids. A close relationship between some pallasites and one of the groups of irons suggests that they may have formed in the semi-molten regions between the metallic cores and rocky outer skins of small planet-like asteroids, whereas mesosiderites originated as mixtures of solid and liquid metal and achondritic rocks of diverse origins.

Recovery of meteorites in Australia

Currently, fragments from a total of 474 distinct and authenticated meteorites have been described from Australia. The material comprises 389 stones (21 achondrites, 366 chondrites and 2 unclassified stones), 71 irons, 13 stony-irons and one meteorite of unknown class. One meteorite, Murchison Downs, previously thought to be distinct has been shown by Bevan & Griffin (1994) to be a transported fragment of the Dalgaranga mesosiderite and is not included in the total. Two hundred and fifty-seven distinct meteorites are currently known from Western Australia, 123 from South Australia, 48 from New South Wales, 20 from Queensland, 12 from the Northern Territory, 10 from Victoria and 4 from Tasmania. Discoveries include the first lunar meteorite, Calcalong Creek, found outside of Antarctica (Hill *et al.* 1991).

Only thirteen well-documented observed meteorite falls have been recorded from Australia (Bevan 1992a). The most recently recovered fall (Fig 3) is a single stone of an ordinary chondrite weighing 488.1 grams, that fell on Binningup beach in Western Australia on 30 September, 1984 (Bevan *et al.* 1988). Several large fireballs, some associated with sonic phenomena, from which meteorites may have been deposited, have been recorded in Australia over the last few years (*e.g.* see McNaught 1993). However, no known material that can be linked to these events has been recovered. A list of the authenticated observed meteorite falls from Australia is given in Table 1. One of the most recent discoveries is a 34 kg mass of ordinary chondrite found near Broken Hill in December 1994 (Grossman 1996)

In Australia, most chance meteorite recoveries, or *finds*, have resulted from the clearing of land for agriculture and pastoralism, and also mining and prospecting activity. The distribution of meteorite falls and finds in Australia is shown in Fig 7. The general lack of discoveries in tropical Australia (north of latitude 23° S) probably reflects a climate and physiography that are not conducive to the preservation and recognition of meteorites, respectively. As noted by Mason (1974) and Bevan (1992a), there remain surprisingly few documented discoveries from central Australia and Queensland.

To date, the largest single mass of meteorite found in Australia is an 11.5 tonne fragment of the Mundrabilla iron found in 1966 on the Nullarbor Plain in Western Australia (Wilson & Cooney 1967). Since the discovery of this mass, more than twelve additional masses of the same meteorite totalling more than 22 tonnes have been recovered from a large area of the central Nullarbor in Western Australia (*e.g.* see De Laeter 1972; De Laeter & Cleverly 1983; De Laeter & Bevan 1992 and references therein).

Five meteorites (4 irons and 1 stony-iron) are associated with meteorite impact craters (Bevan 1992a, 1996). Figure 7 shows the locations of the Dalgaranga, Veevers, Wolfe Creek, Boxhole and Henbury impact craters. Mount Darwin crater in Tasmania (Fig 7) is undoubtedly of impact origin but no meteorites have been collected (Fudali & Ford 1979). An additional small crater, the Snelling crater, has recently been discovered in Western Australia (E S Shoemaker, *pers. comm.*). However, no meteorites are reported to have been collected from the locality. Throughout Australia another eighteen larger structures are known to varying degrees of certainty to be the deeply eroded remains of giant meteorite or asteroidal impact craters (Shoemaker & Shoemaker 1988, 1996). No meteoritic material is known from these sites although there is, in many cases, abundant evidence of meteorite impact that may include characteristic macroscopic shatter-cones, microscopic shock-metamorphic effects in the target rocks, and noble metal geochemical anomalies.

Table 1.
Australian observed meteorite falls (in chronological order)

Name	Date of fall	class	State	co-ordinates
Tenham	(spring) 1879	L6	Qld	25° 44'S 142° 57'E
Rockhampton*	(spring) 1895	stone	Qld	23° 23'S 150° 31'E
Emmaville	1900	Eucrite	NSW	29° 28'S 151° 37'E
Mount Browne	17.7.1902	H6	NSW	29° 48'S 141° 42'E
Narellan	8.4. 1928	L6	NSW	34° 3'S 150° 41' 20"E
Moorleah	Oct. 1930	L6	Tas	40° 58.5'S 145° 36'E
Karoonda	25.11.1930	CK4	SA	35° 5'S 139° 55'E
Forest Vale	7.8.1942	H4	NSW	33° 21'S 146° 51' 30"E
Millbillillie	Oct. 1960	Eucrite	WA	26° 27'S 120° 22'E
Woolgorong	20.12.1960	L6	WA	27° 45'S 115° 50'E
Wiluna	2.9.1967	H5	WA	26° 35' 34"S 120° 19' 42"E
Murchison	28.9.1969	CM2	Vic	36° 37'S 145° 12'E
Binningup	30.9.1984	H5	WA	33° 09' 23"S 115° 40' 35"E

*specimen lost

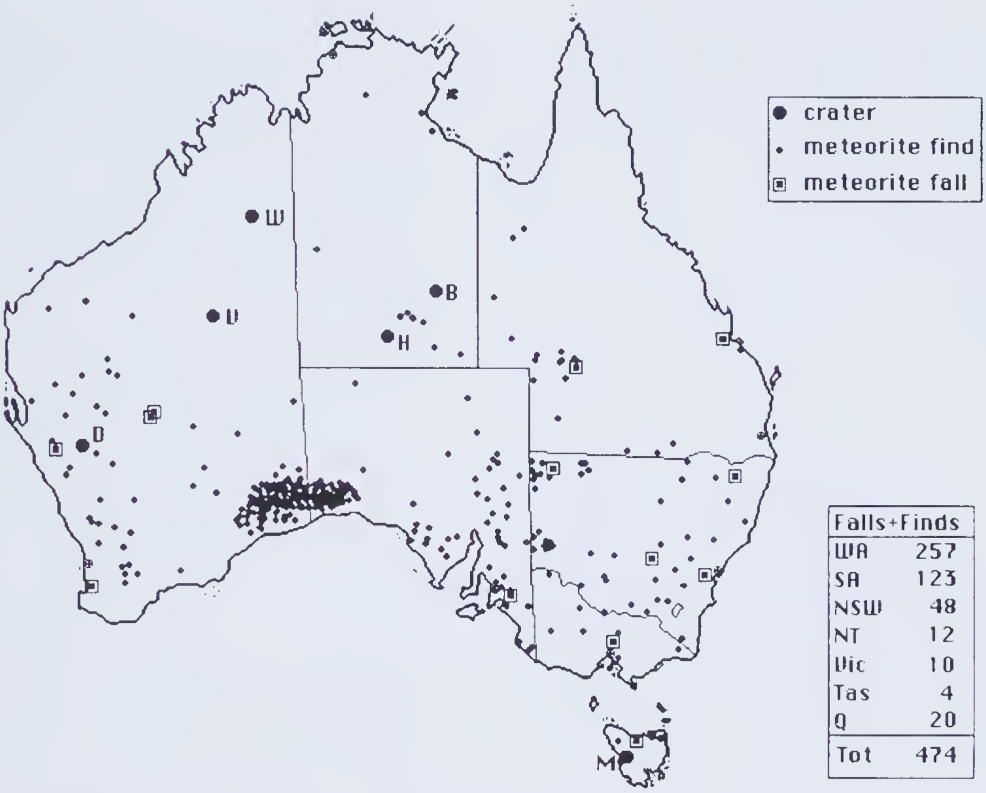

Figure 7. Geographical distribution of meteorite finds and observed falls in Australia and sites of five meteorite impact craters associated with meteorites, Wolfe Creek (W), Dalgaranga (D), Veevers (V), Henbury (H), Boxhole (B), and one crater, Mount Darwin (M), at which meteorites are lacking.

The Nullarbor Region

The anomalously large number of meteorites found in the Nullarbor Region (Fig 7) does not mean that more meteorites have fallen there than anywhere else in Australia, but reflects an unique physiographic environment and a sustained research effort to recover meteorites from the region. The Nullarbor Region is coincident with a geological structure, the Eucla Basin, that straddles the border between South Australia and Western Australia. The sedimentary basin comprises essentially flat-lying limestones of Lower-Middle Miocene Age (*ca.* 15 Ma) outcropping over an area of *ca.* 240,000 km^2. (Lowry 1970). The arid to semi-arid climate of the Nullarbor that has persisted for tens of thousands of years or more, combined with a lack of vegetation and pale country rock, has made the Nullarbor ideal for the prolonged preservation and easy recognition of meteorites. Essentially, meteorites have been accumulating in the Nullarbor since climatic conditions allowed for their preservation. Moreover, in the Nullarbor there is good evidence to suggest that meteorites are lying on, or near, the surfaces on which they fell and that, physiographically, the region has remained essentially undisturbed for at least the last 30,000 years (Benbow & Hayball 1992).

Many of the early meteorite recoveries from the Nullarbor resulted from a programme of search and recovery by personnel from the Kalgoorlie School of Mines (see Cleverly 1993 and references therein), although numerous recoveries have been made by rabbit trappers, notably the Carlisle family from Kalgoorlie (Bevan 1992a). Until recently, there were few meteorites known from the area of the Nullarbor in South Australia. However, collecting by rabbiters and prospectors has resulted in a great number of new recoveries from the area that account for most of the large increase from the 50 meteorites reported by Bevan (1992a) to the current 123 known from South Australia. Unfortunately, most of this South Australian material now resides in collections outside of Australia.

Nomenclature

The described meteorites from the Nullarbor Region now account for more than 50 % of all meteorites known from Australia. As meteorites are named after the geographical localities where they are found, the general lack of geographical names in the Nullarbor, and the great number of new recoveries has caused difficulties for meteorite nomenclature. The problem has been overcome by the introduction of a system of meteorite nomenclature based on geographically named areas. Seventy-four named areas have been delineated (47 in Western Australia; 27 in South Australia) in the Nullarbor Region and new and distinct meteorites take the name of the area in which they are found and a three digit number (*e.g.* Cook 005), usually in chronological order of discovery (Bevan & Binns 1989a; Bevan & Pring 1993). Some nomenclatural anomalies have occurred and these include the Haig, Rawlinna (stone), Cook 003 and Maralinga meteorites, the localities of which lie outside the newly designated areas with the same names.

Palaeoclimatic information from meteorites in the Nullarbor Region

As soon as meteorites enter the Earth's atmosphere they are subject to contamination from, and alteration by, the terrestrial environment. Prolonged weathering transforms many of the minerals in meteorites, masks their original textures, redistributes elements, and eventually destroys them. However, the processes of weathering leave a terrestrial 'fingerprint' in meteorite finds that may be used in climatic research. Meteorites that survive prolonged weathering are potential recorders of environmental conditions during their period of terrestrial residence. Although in its infancy, the use of ancient Nullarbor meteorite finds as indicators of palaeoclimate is yielding promising results.

Recent research on meteorites from the Nullarbor and other hot desert regions of the world for which terrestrial age data are available (Jull *et al.* 1990; Jull *et al.* 1995) has suggested that the weathering characteristics of ancient meteorite finds may reflect the climatic conditions within a millennium or so of their fall (Bland *et al.* 1995a,b). This discovery has stimulated a completely new area of palaeoclimatic research, and the Nullarbor region is proving to be one of the most significant areas of the world for the use of meteorites as palaeoclimatic indicators.

Within the limits of the data currently available (Jull *et al.* 1995), the distribution of ^{14}C terrestrial ages of ordinary chondritic meteorites from the Nullarbor Region show an apparently uninterrupted exponential decrease from the present day to around 30 ka BP (Fig 8). The oldest terrestrial age of a stony meteorite yet published from the Nullarbor (27±1.4 ka) is in good agreement with the estimated age (<30 ka) of the present calcareous clay cover of the Nullarbor (Benbow & Hayball, 1992).

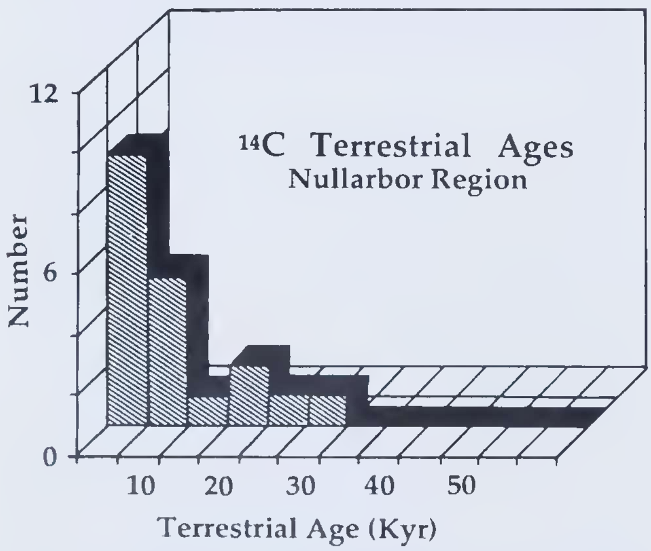

Figure 8. Distribution of ^{14}C terrestrial ages of chondritic meteorite finds from the Nullarbor Region of Australia (after Jull *et al.* 1995).

The preservation and accumulation of meteorites as the result of prolonged aridity in the Nullarbor from *ca.* 30 ka BP is consistent with palaeoclimatic evidence from a wide variety of geomorphological, palaeontological and biological studies of the region. For example, a number of workers, notably Thorne (1971), have suggested on the basis of faunal remains from caves that the climate of the Nullarbor has not changed significantly during the last 20 ka (*e.g.* see Wyrwoll 1979; Davey *et al.* 1992 and references therein). However, pollen from three caves in the Nullarbor examined by Martin (1973) indicated that the period 20 ka to *ca.* 10-8 ka BP was slightly more arid than that of today, with annual rainfall averaging *ca.* 180 mm. The palynological evidence suggests that from around 10-8 ka BP to 5-4 ka BP the rainfall increased on the Nullarbor, and has since maintained an annual average of about 250 mm. Further evidence from pollen from the dessicated guts of some dated mummified mammalian carcasses (Ingram 1969), supports the conclusion that the annual rainfall in the Nullarbor Plain area has remained roughly constant since about the middle Holocene (*ca.* 5 ka BP).

Currently, the Nullarbor has no active surface drainage. However, higher lake levels and relict stream courses traversing the region testify to a period of greater effective precipitation (Jennings 1967a,b, 1983; Lowry 1970; Lowry & Jennings 1974; Graaff *et al.* 1977; Street-Perrott & Harrison 1984). When these channels were last active is unknown, although U-series dating of calcite speleothems from Nullarbor caves (Goede *et al.* 1990) suggests that no significant calcium carbonate deposition has taken place during the last 300-400 ka. Presently, active deposition of speleothems in Nullarbor caves is almost exclusively gypsum and halite (Goede *et al.* 1990; Goede *et al.* 1992). As a mechanism for halite deposition, Goede *et al.* (1992) suggest that periodic changes to slightly higher effective precipitation in the Nullarbor re-initiated percolation and, provided that the seepage was subject to strong evaporation in the cave atmosphere, led to the deposition of halite speleothems.

U-series ages of halite speleothems from the Nullarbor have been reported by Goede *et al.* (1990, 1992). One large (2.78 metres long) broken salt stalagmite from Webbs Cave gave a 'bulk' age indicating prolonged deposition during the Late Pleistocene between *ca.* 37 ka and 20 ka BP (Goede *et al.*, 1992). Previous dating (Goede *et al.*, 1990) of a small (0.16 m) halite stalagmite from the same cave yielded an age of 2.5±1.2 ka indicating that there have been at least two phases of halite speliothem formation in Webbs Cave within the last 37 ka.

The work of Goede *et al.* (1990, 1992) shows that during the Late Pleistocene (*ca.* 30-20 ka BP) and again in the Holocene (*ca.* 2.5 ka BP) there were minor changes to more humid conditions in the Nullarbor following periods of prolonged aridity, and support the conclusions of Martin (1973) and Lowry & Jennings (1974). Significantly, the age range of the oldest salt stalagmite (37-20 ka) from Webbs Cave overlaps with the apparent onset of accumulation of stony meteorites from around 30 ka BP on the Nullarbor surface. If any stony meteorites significantly older than 30 ka exist in the Nullarbor, it is possible that they are buried in the calcareous clay cover. However, it should be noted that $^{26}Al/^{53}Mn$ dating of the Mundrabilla iron meteorite by Aylmer *et al.* (1988) gave a terrestrial age >1 Ma, indicating that it is the oldest meteorite fall yet recovered from the Nullarbor.

Bland *et al.* (1995a, b) have attempted to quantify the state of weathering of a number of ordinary chondrite finds from the Nullarbor using ^{57}Fe Mössbauer spectroscopy. By comparing the abundance of ferric iron oxide/oxyhydroxide species in individual meteorites against terrestrial age, Bland *et al.* (1995b) suggest that meteorite weathering is sensitive to climate at the time of fall. Moreover, meteorites appear to obtain their weathering characteristics within *ca.* 1000 years of fall. Gradual weathering rates, like those that have persisted in the Nullarbor, allow the formation of stable surface oxide layers, and a reduction in the porosity of the meteorites that provides protection against further significant weathering during periods of more effective precipitation. Moreover, carbonates derived by the meteorite from the Nullarbor limestone also fill pore space in some stones (Bevan & Binns 1989b). It appears that once a stony meteorite reaches a state of temporary equilibrium after initial weathering, the energy of the surrounding environment needs to be raised significantly to alter the remains further, or destroy them.

Figure 9 shows a plot of total ferric oxidation (%) in Nullarbor H-group ordinary chondrites against terrestrial age (after Bland *et al.* 1995b). Periods of climatic change derived from biological and geomorphological studies outlined above are marked for comparison. Even within the limits of the small data set currently available there is a remarkable co-incidence between the 'rustiness' of chondritic meteorites as measured by Mössbauer (Bland *et al.* 1995b), and periods of alternately higher and lower effective precipitation in the Nullarbor during the Late Pleistocene and Holocene.

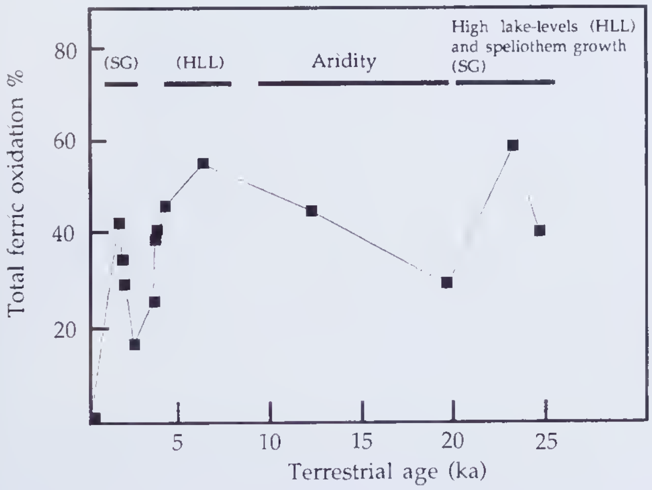

Figure 9. Plot of total ferric oxidation (%) of weathered H-group ordinary chondrites from the Nullarbor Region of Australia as determined by Mössbauer against their ^{14}C terrestrial ages. Marked above are significant palaeoclimatic events in SW Australia for the same period; see text for references (after Bland *et al.* 1995b)

Jull *et al.* (1995) have made a preliminary study of the carbonates from some weathered ordinary chondrites from the Nullarbor. The results show that there are some variations in δ^{13}C, and there is a weak correlation of δ^{13}C and carbonate content with terrestrial age that may be linked to palaeoclimatic events.

Recent recoveries of rare meteorites in Australia

Bevan (1992a) listed a number of rare meteorites recovered from Australia. The most significant of the observed falls (Table 1) are the two carbonaceous chondrites Murchison [CM2] (CM= Mighei type carbonaceous chondrite) and Karoonda [CK4] (CK= Karoonda type carbonaceous chondrite; see Bevan 1992a and references therein). Carlisle Lakes, a previously anomalous and ungrouped chondritic meteorite find from the Nullarbor (Binns & Pooley 1979) has recently been shown to belong to an entirely new group of chondrites including an observed fall, Rumuruti, from Kenya (Schulze *et al.* 1994). The new group of chondrites, known as the 'R' group (after Rumuruti), includes several other meteorites from Antarctica and one from the Reg El Acfer in North Africa (Bischoff *et al.* 1994; Rubin & Kallemeyn 1989, 1993, 1994; Schulze *et al.* 1994). A new group of carbonaceous chondrites, the CR group (named after the type meteorite Renazzo), has been described (*e.g.* see Weisberg *et al.* 1993). Spettel *et al.* (1992) have suggested that Loongana 001, an unusual chondrite found in 1990 in the Western Australian Nullarbor is related to the CR group. However, Kallemeyn & Rubin (1995) have shown that the meteorite does not belong to any of the established carbonaceous chondrite groups and along with the Coolidge chondrite found in the USA, forms a distinct grouplet of carbonaceous chondrites related to the CV group (named after the type meteorite Vigarano).

Bevan (1992a) noted that out of the main groups or sub-types of meteorites then known, only ten were not represented in collections from Australia. In the last three years, however, several ordinary chondrites of petrologic type 7 have been described providing examples previously missing (Wlotzka 1994), along with a possibly new petrologic type 2 (?) member of the CV group of carbonaceous chondrites, Mundrabilla 012 (Ulff-Møller *et al.* 1993). One enstatite chondrite of type 7, Forrest 033, has been recorded (Wlotzka 1994). A new CV3 chondrite, Denman 002, has been described from the South Australian Nullarbor (Dominik & Bussy 1994).

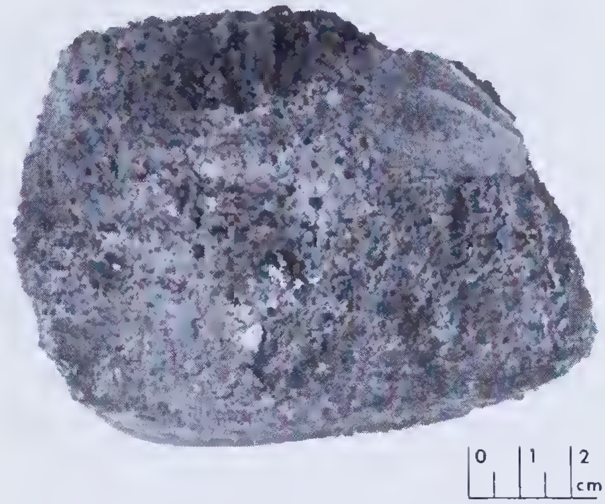

Figure 10. Mass (1.536 kg) of the Cook 003 CK4 chondrite found in the South Australian Nullarbor. The knobbly surface is due to large protruding chondrules (photograph by K Brimmell).

Sleeper Camp 006 and Cook 003 (Fig 10), two stones found in the Western Australian and South Australian Nullarbor respectively, are additional CK4 chondrite finds. Cook 003 may be paired with an earlier reported discovery, Maralinga (Geiger *et al.* 1992). Two other recoveries from the Nullarbor, Camel Donga 003 and Watson 002 are the first known examples of CK3 chondrites from Australia and their reported find-sites are sufficiently far apart to discount pairing (Wlotzka 1993a,b).

In terms of achondrites, Calcalong Creek (Hill *et al.* 1991; Wlotzka 1991), reportedly discovered within the strewn field of the previously known Millbillillie achondrite (eucrite) in Western Australia, is the first lunar meteorite found outside of Antarctica. Calcalong Creek is a polymict lunar breccia with the highest KREEP component of any known lunar meteorite (Hill *et al.* 1991). New achondrites from the Nullarbor include several howardites; Camel Donga 004, Hughes 004, Hughes 005, Old Homestead 001, Mundrabilla 018 (Wlotzka 1995) and Muckera 002. Old Homestead 001 and Mundrabilla 018 were found close together, as were Hughes 004 and 005 and these may be fragments of the same fall. The fragments constituting Muckera 002 were found near the site of discovery of the Muckera meteorite (now Muckera 001) which is also a howardite. Eagles Nest found in central Australia and Reid 013 from the Nullarbor, two new examples of brachinaites (olivine-rich achondrites named after the type meteorite found at Brachina in South Australia) have been found (Wlotzka 1992b,1993b). Reid 013 is remarkably similar to Nova 003, a meteorite the locality of which is uncertain (Wlotzka 1993b). Three new ureilites, Hughes 007, Hughes 009 and Nullarbor 010, have been found in the Nullarbor and the latter meteorite is similar to Nova 001, an ureilite originally reported as found in Mexico although now considered to be of uncertain location (Wlotzka 1993a).

A new lodranite (an anomalous stony-iron meteorite of rare type possibly related to the ureilite achondrites), named Gibson, has been found in north-western Australia and is the first meteorite of its kind found in Australia (Wlotzka 1992b). Since 1992, two important new masses of iron meteorites have been reported. Two distinct group IIE irons, Watson (93 kg) (Olsen *et al.* 1994) and Miles (265 kg), have been reported from the South Australian Nullarbor and Queensland, respectively (Wlotzka 1992a, 1994). A new iron, Hidden Valley weighing 7 kilograms, belonging to chemical group IIIAB was also found in Queensland in 1991 (Wlotzka 1994). These discoveries bring the total number of distinct irons reported from Australia to 71.

Meteorite groups and types remaining to be reported from Australia include chondrites belonging to EH3-4, EL5, CI, CK5, CO3, and a possibly new 'CH' group of carbonaceous chondrites (Bischoff *et al.* 1993), and achondrites belonging to the calcium-poor groups, aubrites and diogenites.

Summary

Over the last ten years, the number of meteorites known from Australia has doubled. Even so, the large number of recent recoveries probably represents a small fraction of the meteorites that are available for collection in the country's arid and semi-arid zones. Together with meteorites from other hot and cold deserts of the world, the concentration of meteorites in the Nullarbor (Fig 11) is already providing a valuable research resource. New groups of meteorites are being recovered that are extending our knowledge of the early Solar System; statistical studies are providing information on the flux of meteorites with time; and terrestrial age dating combined with weathering studies are yielding palaeoclimatic information about the areas of meteorite accumulation.

Figure 11. Crusted fragment of the Camel Donga eucrite achondrite shower at the site of discovery on the Nullarbor Plain (lens cap for scale is 5 cm diameter).

Although various dating techniques have been applied to a wide variety of terrestrial materials (*e.g.* see Lamb 1977), one of the major problems of Quaternary palaeoclimatic research is the paucity of dateable materials that can provide an absolute chronology for events. Concentrations of meteorites, such as in the Nullarbor Region, provide dateable materials of a variety of terrestrial exposure times spanning the accumulation period, and may allow changes in weathering rates through time to be estimated. The pioneering work of Bland *et al.* (1995 a,b), Jull *et al.* (1995) and others is demonstrating that weathered stony meteorites have the potential to provide useful palaeoclimatic information over the period of their accumulation.

The surfaces of ancient stony meteorites from the Nullarbor frequently possess variably thick carbonate coatings (caliches) that have been derived via the calcareous clay from the limestone country rock (Bevan & Binns 1989 a,b). Additionally, extensively weathered Nullarbor stony meteorites contain veins and pockets of carbonate that have penetrated the fabric of the meteorite along cracks and pores. Detailed mineralogical and isotopic studies of carbonates from Nullarbor meteorites have yet to be performed. However, measurements of the stable isotopic compositions of these evaporitic deposits may aid in determining the source materials and the mechanisms of calichification, related to temperatures of deposition. Since these carbonates are likely to have grown much more rapidly than marine carbonates they could be used to derive high resolution temperature profiles, and offer possibilities of palaeotemperature assessment over the time span of meteorite accumulation in the Nullarbor.

Meteorites found in Australia are playing an increasingly important role in fundamental research across a wide spectrum of disciplines both within the country and overseas. There is every reason to believe that dense accumulations of meteorites, as in the Nullarbor, exist throughout the arid zone of Australia. Eventually, Australia may outstrip Antarctica and the USA as a source of meteorite recoveries. This seemingly unlikely source of Quaternary palaeoclimatic information provides yet another aspect to meteorite research in Australia. What studies of ancient meteorite finds from Australia are likely to reveal in detail about past climates is unknown. Like all fundamental scientific research, one never knows how useful it will be until it is done!

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